

1. You're at an astronomy meeting, and a person comes up to you all about a new discovery: the central star of the planetary nebula PN 144.5+06.5 is a multi-mode pulsator! (That's a vibrating star, which changes its brightness on a timescale of minutes. By studying the periods, you can probe the star's interior structure in much the same way that a seismologist can use sound waves to study the interior structure of the Earth.) A 24-in telescope will do the job, but you do need to obtain a long time series of data to nail the periods without aliasing. So you begin to wonder – how long a time sequence can be obtained using observations from State College? After cursing the fact that the PN community names its objects via their *Galactic* coordinates, you begin to work the problem.

a) What is the best time of year to observe the object (i.e., when is it on the meridian at midnight)?

The first thing to do is convert the PN's Galactic coordinates to equatorial coordinates. Slide 23 has the equations to do this. First, the declination can be calculated through

$$\delta(1950) = \arcsin \{ \cos b \sin(\ell - \ell_0) \sin \delta_0 + \sin b \cos \delta_0 \}$$

and then the right ascension can be found using

$$\alpha(1950) - \alpha_0 = \arccos \left\{ \frac{\cos b \cos(\ell - \ell_0)}{\cos \delta} \right\}$$

where $\alpha_0 = 282.25^\circ$, $\delta_0 = 62.6^\circ$, and $\ell_0 = 33^\circ$. The star's equatorial coordinates are then $\alpha(1950) = 4:02:01.8$, $\delta(1950) = +60:47:19$.

Next the coordinates should be precessed to the current equinox. To a good approximation, the 1950 coordinates should be incremented by

$$\alpha(2017) = \alpha(1950) + (3.07234 + 1.3365 \sin \alpha \tan \delta) \Delta t$$

and

$$\delta(2017) = \delta(1950) + (20.0468 \cos \alpha) \Delta t$$

where $\Delta t = 66$ yr. The equatorial coordinates of the object are $\alpha(2017) = 4:07:48.68$, $\delta(2016) = +60:58:05.4$. The best time of year to observe the object is when it's on the meridian at midnight. According to the Astronomical Almanac, that's halfway between Nov 22 and Nov 23. So either date is best.

b) How long will the object be above 2 airmasses? (That's the point where optical observations generally begin to deteriorate.)

Two airmasses corresponds to a zenith angle of

$$\mathcal{M} = \sec z \implies \cos z = \frac{1}{\mathcal{M}} \implies z = 60^\circ$$

(Actually, with the second-order term, the angle is 60.12° , but obviously, that's a very small correction.) The altitude of an object at $z = 60^\circ$ is obviously $a = 90 - z = 30^\circ$. The hour angle at which the object is at $a = 30^\circ$ is then given by

$$H = \arccos \left\{ \frac{\sin a - \sin \delta \sin \phi}{\cos \delta \cos \phi} \right\}$$

Plugging in the numbers for State College (where the latitude, $\phi = 40.79$), gives $H = 101^\circ$, or 6.74 hours. The object is therefore above 2 airmasses for almost 13.5 hours.

c) There are three definitions of twilight: civil twilight (where the Sun is 6° below the horizon), nautical twilight (12° below the horizon), and astronomical twilight (18° twilight). In practice, this means that the sky begins to brighten shortly after astronomical twilight, and becomes too bright for most observations by nautical twilight. How many hours between astronomical twilights are there when the object transits at midnight? How many hours between nautical twilights? How long can one observe the planetary nebula?

According to the *Astronomical Almanac*, on Nov 22 at $\phi = 40^\circ$, astronomical twilight ends at 18:24 and begins at 5:31. So there are 11 hours 7 minutes available for dark sky observations. Similarly, nautical twilight begins at 17:51 and ends at 6:04, giving a window of 12 hours and 13 minutes for observations. So, during the Thanksgiving break, you can literally observe the object all night. (Which I've done – the object's more common name is NGC 1501, and while a postdoc, I spent one Thanksgiving break just sitting on the object, taking 90 second exposures all night for 3 nights.)

2. On July 1, you are at a telescope measuring the internal dynamics of the spiral galaxy NGC 6946. The object, which is sometimes called “the Fireworks Galaxy,” has hosted 8 supernovae in the past century and has equatorial coordinates of $\alpha(2000) = 20:34:52$, $\delta(2000) = +60:09:14$. You measure the radial velocity of a globular cluster within the galaxy to be $\sim 150 \text{ km s}^{-1}$. What is this cluster's true barycentric radial velocity? (In other words, what component of the observed velocity is due to the Earth's motion about the Sun?) Hint: the problem is easy. Section B of the *Astronomical Almanac* has all the information you need. All you need to do is find it.

What you need is the projection of the Earth's motion ($\dot{X}, \dot{Y}, \dot{Z}$) onto the direction of the galaxy. In other words

$$V = (\dot{X}, \dot{Y}, \dot{Z}) \cdot \begin{pmatrix} \cos \alpha \cos \delta \\ \sin \alpha \cos \delta \\ \sin \delta \end{pmatrix}$$

According to the 2017 version of the *Astronomical Almanac*, on July 1 $\dot{X} = +15,963,651$, $\dot{Y} = -5,262,767$, and $\dot{Z} = -2,282,219$ in units of 10^{-9} A.U. per day. So the calculation is straightforward (although, to be perfectly correct, you should first precess the coordinates onto the 2017.5 system). The heliocentric correction to the velocity measurements is about $+9 \text{ km s}^{-1}$.

(Note that one should always double-check the sign of these solutions. In this case, the date of observation is July 1, which means 18^h is on the meridian at midnight. The object is at

located at about 20.5^h , so it will be on the meridian at midnight in a bit over a month. So the Earth is moving *towards* the object. One therefore needs to add velocity to the object.)

3. The Martian north pole is at $\alpha(2000) = 21:11:06$, $\delta(2000) = +52:55:48$. The Phoenix rover landed at (Martian) latitude $\phi = +68:13:08$. Is the star α Centauri in the background on any of the images taken by the Phoenix? (In other words, does α Cen get above the horizon?)

We need to transform the equatorial coordinates of α Centauri into the Martian equivalent of declination. We can do this by analogy to the conversion between equatorial and ecliptic coordinates. If we form a spherical triangle using the north celestial pole, the Martian pole, and the object, then

$$\sin \delta_M = \sin \delta \cos \epsilon - \cos \delta \sin \alpha \sin \epsilon$$

where δ_M is the Martian declination, and $\epsilon = 37.07$ is the angular distance between the Martian pole and the Earth's pole. From the Astronomical Almanac, the equatorial coordinates of α Cen (on Earth) are $\alpha(2016.0) = 14:40:44.0$, $\delta(2016.0) = -60:54:10$. Plugging in the numbers gives $\delta_M = -30.54^\circ$. Since the Phoenix is located at $\phi = 68.22^\circ$, α Cen is not quite visible.

4. The Hobby-Eberly Telescope (HET) is a 10-m class optical telescope located at McDonald Observatory in West Texas (longitude 104.0248° W, latitude 30.6798° N). The defining aspect of the HET is that it is not a fully steerable telescope: although the structure can rotate to any azimuth, its zenith angle is permanently fixed at 35° . Objects are therefore tracked as they move across the 6° field-of-view of the primary mirror. FYI: our department owns about 25% of the time on this telescope.

- a) What is the northernmost declination the telescope can observe? What is the southernmost declination it can observe? (Actually, you can push these numbers a degree or two more, if you're desperate and willing to reduce the effective aperture of the telescope, but let's not go there.)

The HET is fixed at a zenith angle of $z = 35^\circ$, and its latitude on earth is $\phi = +30.6798^\circ$. When rotated to point due north, it can therefore observe objects with a declination of $\delta_N = \phi + z = 65.7^\circ$. When pointed due south, the HET can access a declination of $\delta_S = \phi - z = -4.3^\circ$. In other words, the HET can observe objects with declinations between $-4.3^\circ < \delta < 65.7^\circ$, which is a little less than $1/3$ of the sky.

- b) All the instruments on the HET are fiber-fed; in other words, light is focussed onto an optical fiber, which transmits the light to an instrument. The HET's Habital-Zone Planet Finder (HPF) is a high-resolution infrared spectrograph that is fed by a fiber 1.7 arcsec in diameter. Suppose a star is centered onto the HPF's fiber using the 5500 Å light detected by the telescope's guide camera. About how much would you need to offset the HPF from its nominal position to ensure that most of the star's $1.2 \mu\text{m}$ light is collected? (Hint: rather than work things out from first principals, look at the references!)

The quickest way to answer this question is to use the table given by Filippenko 1982, PASP, 94, 715. The HET is set at a zenith angle of 35° , which equates to an airmass $M = \sec z = 1.22$. According to Table 1 in Filippenko, at an altitude of 2 km, $1 \mu\text{m}$ light

will be displaced about ~ 0.43 arcsec from 5500 Å light. (To be perfectly correct, we should then add the (very small) astrometric offset between 1 μm and 1.2 μm , then subtract the (very small) difference arising from the fact that McDonald Observatory (altitude 6,647 ft) is observing through slightly less air than assumed for the calculation (6562 ft). But these differences are well within the noise of the estimate.) So we might expect the infrared image of the star to be offset about 0.43 arcsec, or about a quarter of a fiber diameter from the star's optical image.